Application of Process Modeling and Simulations in Army Rotary Wing Composite Structural Developments

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CHSSI SCALABLE SOFTWARE

COMPOSE

COMPOSITE MANUFACTURING PROCESS SIMULATION ENVIRONMENT

Application of HPCMP CHSSI developed software in ARMY RWSTD.

- Composites and processing in RWSTD
- Process modeling and simulations
- COMPOSE simulations for RWSTD composite structures

Rotary Wing Structures Technology Demonstration (RWSTD)

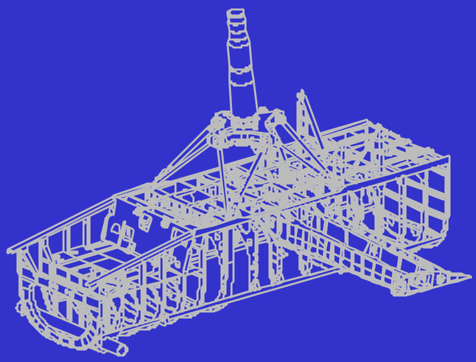
RWSTD OBJECTIVE

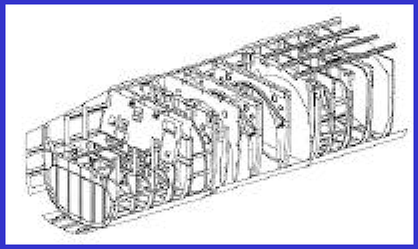
Apply Advanced Structural Tools and Processes in the Design of Large-Scale Assemblies for Rotary Wing Vehicles and Demonstrate Significant Reduction in Cost and Weight

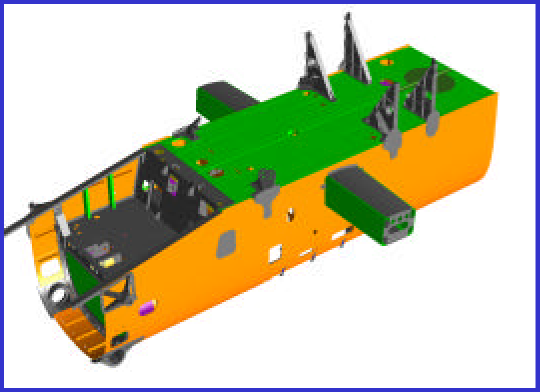
RWSTD GOALS

- Reduce Cost of Ownership of New Technologies
- Smooth and Accelerated Technology Transition to EMD and Production
- Support Apache Affordable Growth Program (AAGP)

RWSTD Design Metrics



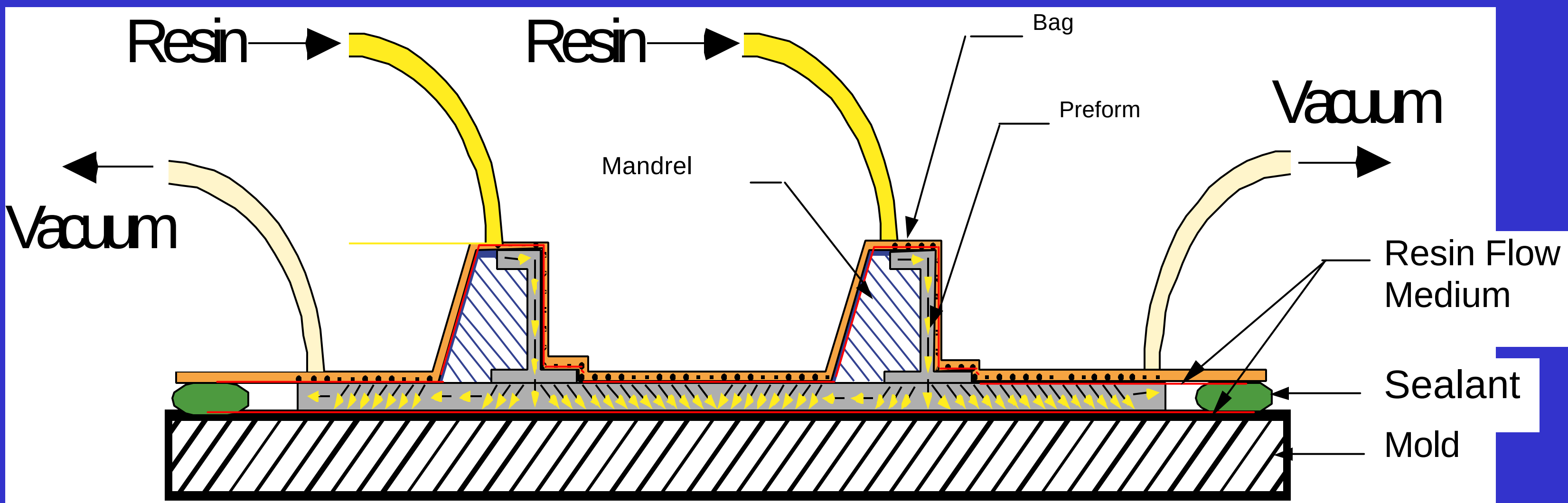




Existing Metal Center Fuselage	*1994 Composite Technology Baseline*	*RWSTD Composite Center Fuselage*
3% Composite (by Wt.)	67% Composite (by Wt.)	74% Composite (by Wt.)
565 Parts	250 Parts	153 Parts
12,100 Fasteners	6,400 Fasteners	2,579 Fasteners
14,660 lb SDGW	19,000 lb SDGW	19,000 lb SDGW
468 lb (512 lb. for 19,000 lb GW)	407 lb	343 lb
16,500 mfg man-hrs	12,565 mfg man-hrs	9,118 mfg man-hrs

Liquid Composite Molding (LCM)

Vacuum Assisted Resin Transfer Molding (VARTM)

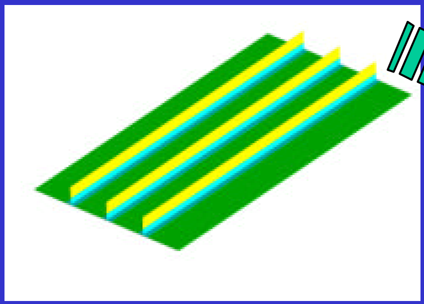


- ✓ Uses one sided tooling
- ✓ Permits rapid prototyping
- ✓ Co-cures and co-bonds sub-assemblies

- Complex structures – Higher risk
- Higher volume fraction – Needs good controls
- Not currently in aerospace

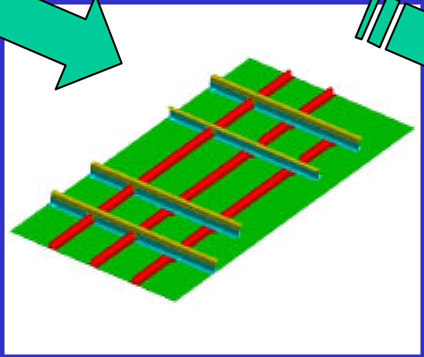
VARTM Risk Reduction Articles

- BUILDING BLOCK APPROACH
- PRELIMINARY DESIGN ALLOWABLES
- DETAILS REPRESENTATIVE OF FULL SCALE ARTICLE



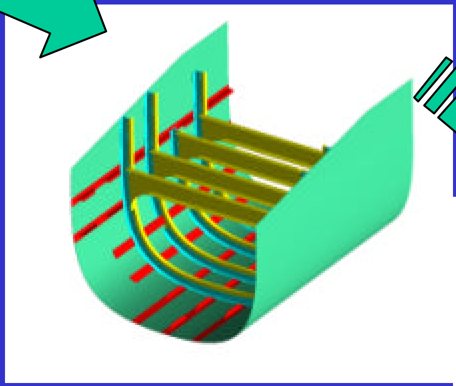
SIMPLE PANEL

5 PANELS
1 WITH CLIPS STITCHED
2 WITH CLIPS STITCHED (ONE FLAWED)
2 WITH CLIPS Z PINNED (ONE FLAWED)



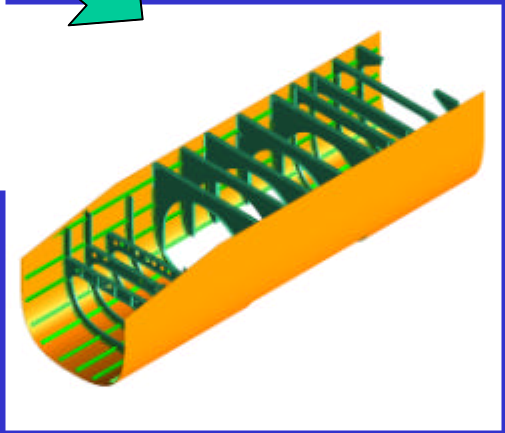
COMPLEX PANEL

3 PANELS
STRINGERS ADDED
TWO CONFIGURATIONS FOR
STRINGER/FRAME PASS THROUGH



FIVE-FOOT SUB-COMPONENT

1 ASSEMBLY
AH64 REPRESENTATIVE STRUCTURE
LESSONS LEARNED FROM PANELS APPLIED



FULL-SCALE CENTER FUSELAGE

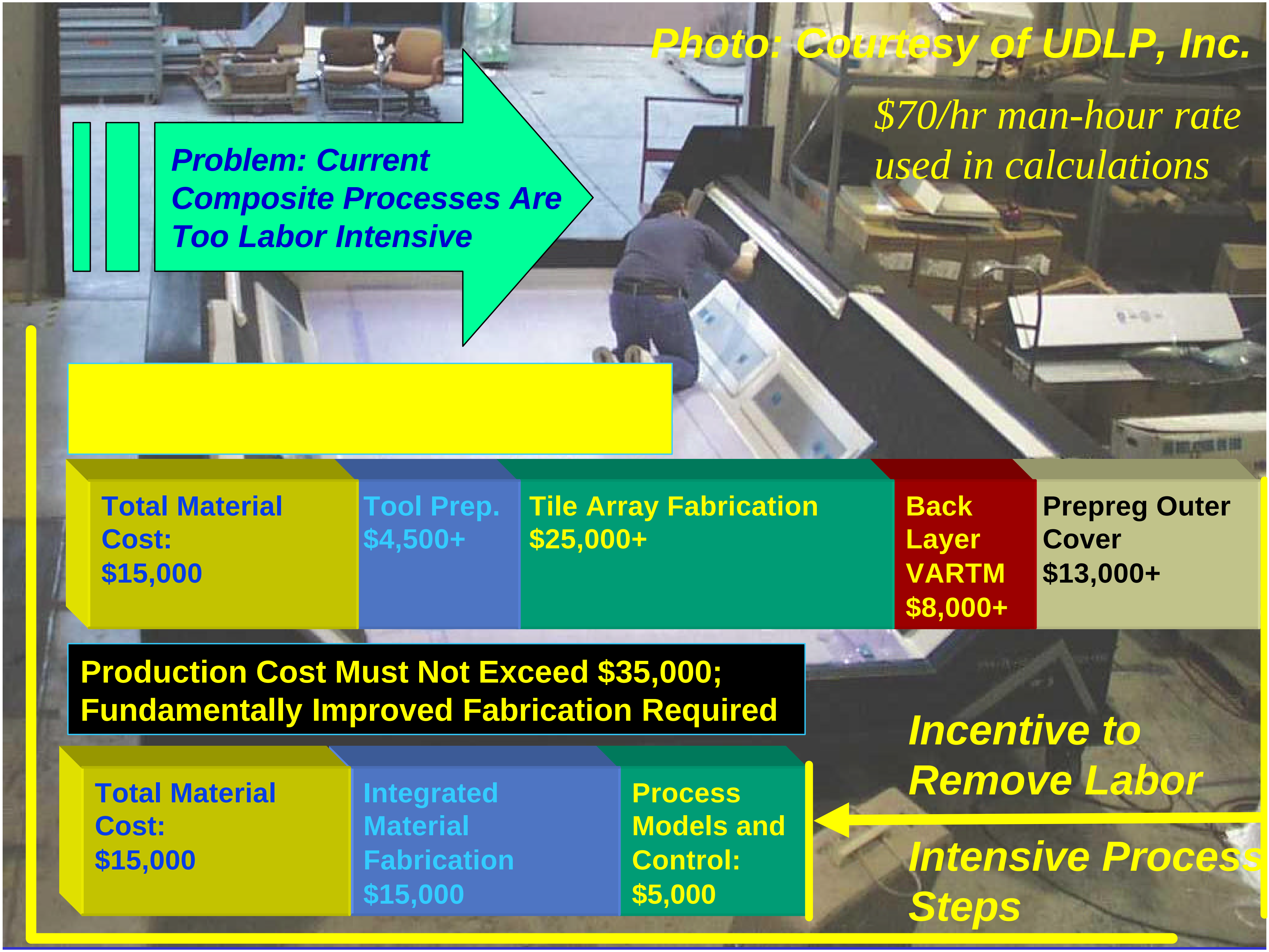


Photo: Courtesy of UDLP, Inc.

$70/hr man-hour rate used in calculations

Problem: Current Composite Processes Are Too Labor Intensive

Total Material Cost: $15,000

Tool Prep. $4,500+

Tile Array Fabrication $25,000+

Back Layer VARTM $8,000+

Prepreg Outer Cover $13,000+

Production Cost Must Not Exceed $35,000; Fundamentally Improved Fabrication Required

Total Material Cost: $15,000

Integrated Material Fabrication $15,000

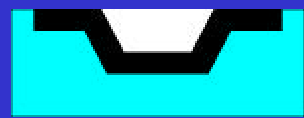
Process Models and Control: $5,000

Incentive to Remove Labor Intensive Process Steps

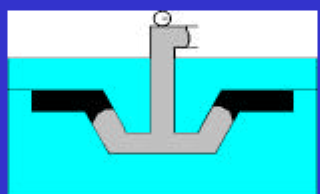
Process Modeling and Simulations

LCM Process

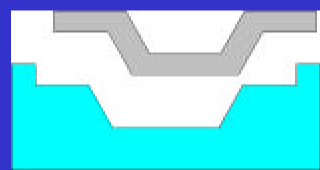
Preform lay-up



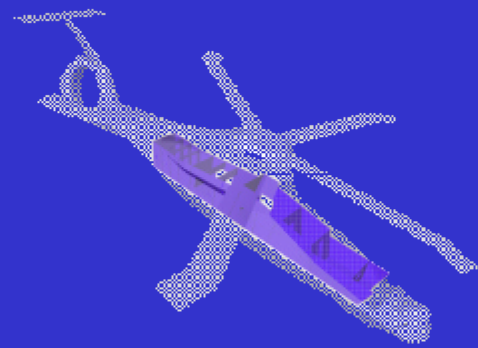
Insert preform into mold



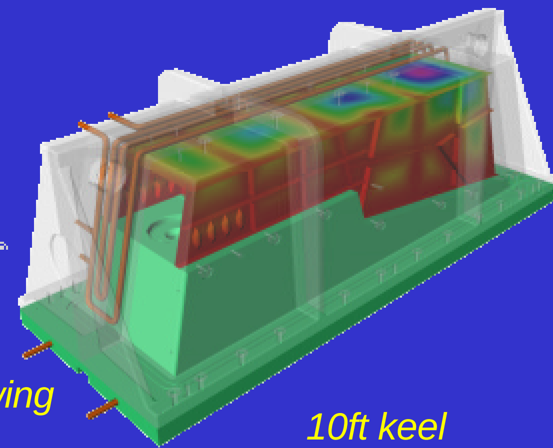
Resin injection/curing



Part removal



Comanche helicopter showing 24ft keel beam section



10ft keel section show in mold

- Trial and error approach
  - Best estimate parameters
  - Difficult and time consuming “re-tool”
  - High process development time and cost
  - Increases man-hour and per pound composite cost

- Intelligent processing approach
  - Resolve potential problems with mold and process before significant tooling investment
  - Accommodate design and process considerations
  - Process modeling and simulations

CHSSI SCALABLE SOFTWARE

COMPOSE

COMPOSITE MANUFACTURING PROCESS SIMULATION ENVIRONMENT

COMPOSE2D: Thin composites (2.5D)

COMPOSE3D: Thick composites (3D)

COMPOSE_CONVERT

COMPOSE_CHECK

COMPOSE_OPTIMIZE

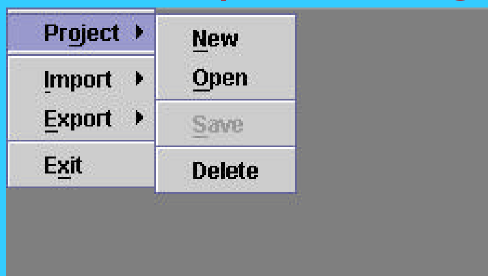
COMPOSE_PARTITION

SGI Origin

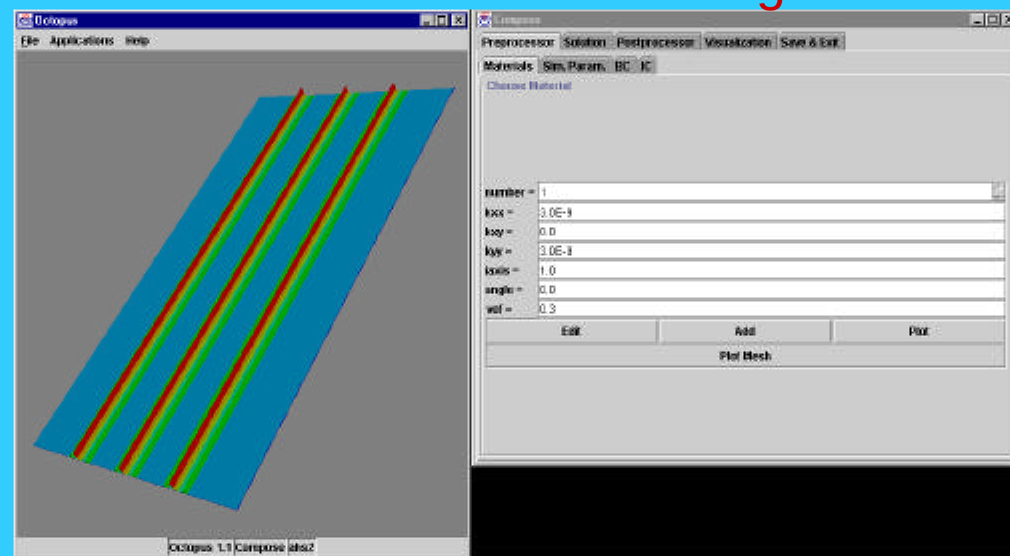
CRAY T3E

IBM-SP

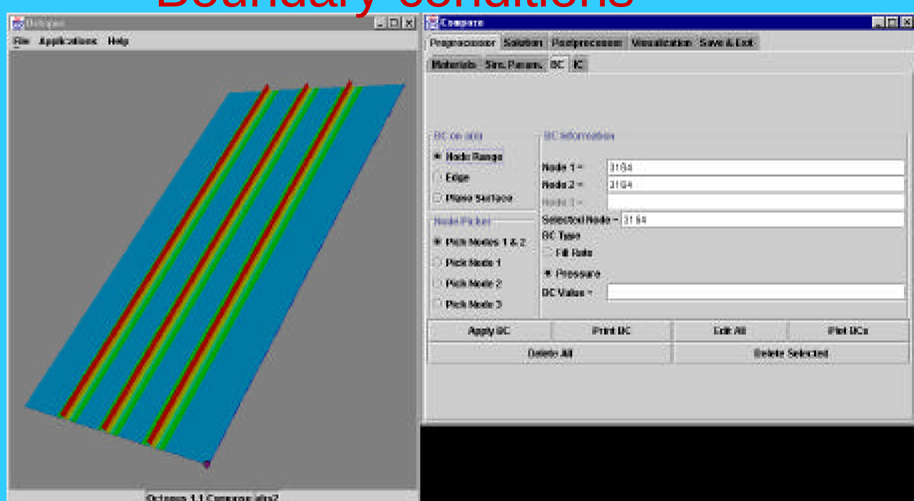
Model processing



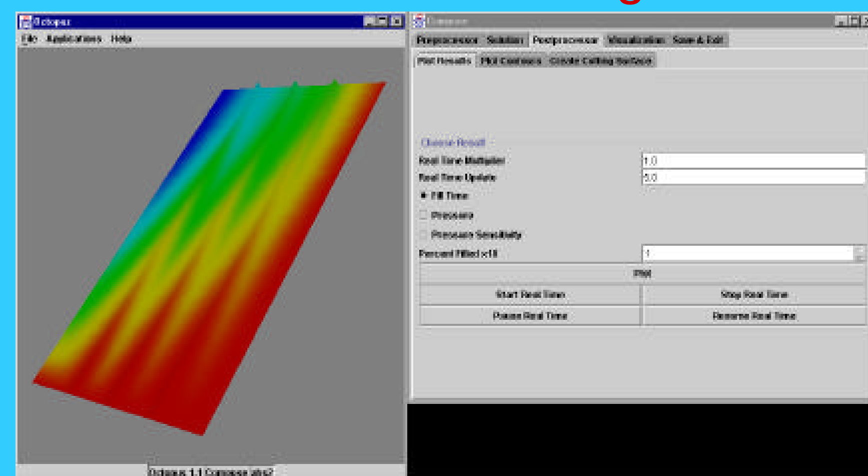
Material property assignment



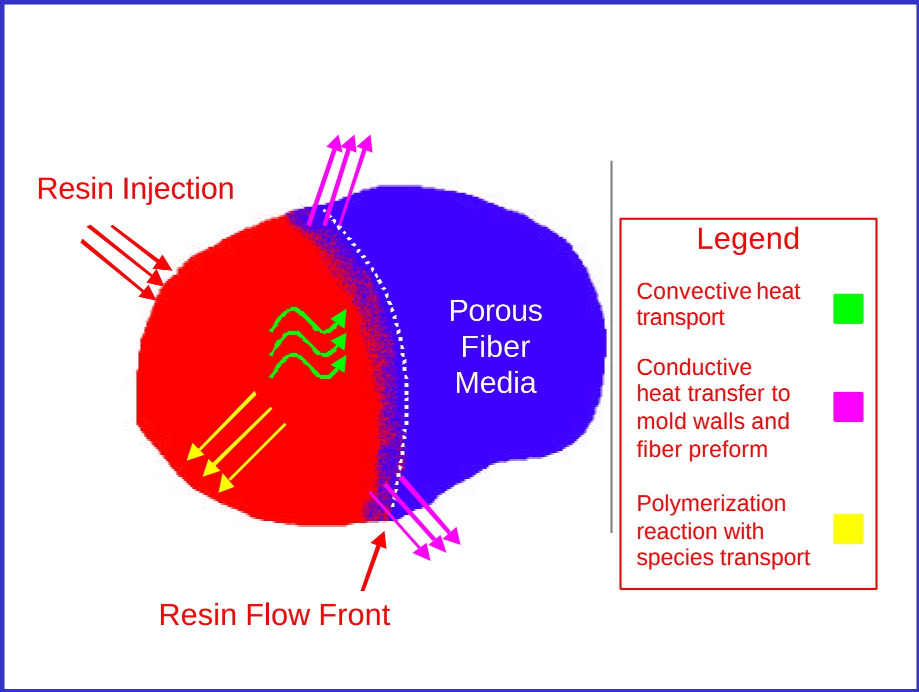
Boundary conditions



Post-Processing



Physical phenomena in LCM processes



- Involves a reactive thermoset polymeric resin permeating a fiber preform
- Manufacturing considerations require complete impregnation within pot-life of resin before initiation of chemical kinetics

In-process sensors and feedback control

Material properties

Testing and experimental validation

Intelligent Composite Manufacturing

Manufacturing process simulations

Resin impregnation

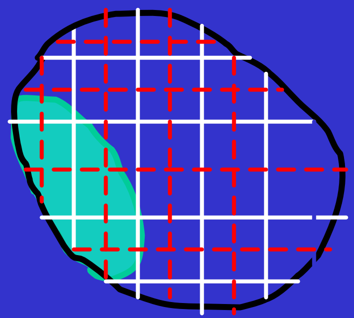
Heat and species transfer

Fiber deformation and compaction
Micro-macro properties

Computational Approaches

- Traditional Explicit FE-CV
  - Quasi-steady approach for the transient problem
  - Solution based on quasi-steady state continuity equation coupled with Darcy's law

$$\nabla \cdot \underline{u} = 0 \qquad \underline{u} = -\frac{K}{m} \nabla P$$



Finite element mesh

Control volumes

- Time increment of the quasi-steady front update restricted by stability considerations
  - Mesh size dictates time step increments
  - Very small computed time increments lead to a larger number of quasi-steady steps for complete impregnation
- Need physically accurate and computationally efficient methodologies for large-scale simulations

Pure Finite Element Method

- Objective of RTM Fiber Impregnation and Mold Filling
  - Conservation of resin mass at any instant of time
  - Determination of resin distribution inside and Eulerian mold cavity
- Pure Finite Element Method
  - Based on transient mass balance equation for resin mass:

$$\frac{d}{dt}\int_{\Omega} \Psi \, d\Omega = \int_{\Omega} \nabla \cdot \left(\frac{K}{m} \nabla P \right) d\Omega$$

Ψ: Fill factor ($0 < \Psi \leq 1.0$) specifies cavity status

Non-impregnated regions $\Rightarrow \Psi = 0$; Resin impregnated regions $\Rightarrow \Psi = 1$

Partially filled regions $\Rightarrow$ Pressure gradients are negligible

P: Pressure; K = Permeability tensor; m : Viscosity of fluid

Pure Finite Element Method

Finite Element Discretization

- Mold cavity discretized and modeled by finite elements
  - – Thin 2D shell elements for thin composite sections
  - – Thick 3D elements for thick composite sections
- Fill factor Ψ: Each node is associated with a fill factor

  Ψ = 1: Completely impregnated node; Ψ = 0: empty node

  Ψ = 1 : for all nodes in an element $\Rightarrow$ completely impregnated element

  Ψ = 0 : for all nodes in an element $\Rightarrow$ completely empty element
- Introduce finite element approximations for Ψ and pressure P

$$\boxed{\begin{aligned} P &= N_i\, P_i \\ \Psi &= N_i \Psi_i \end{aligned}}$$

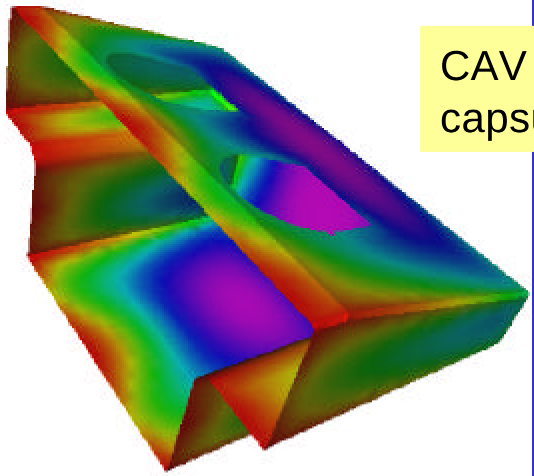
- Galerkin weighted residual formulation of mass balance equation

$$C\dot{\Psi} + [K]P = f$$

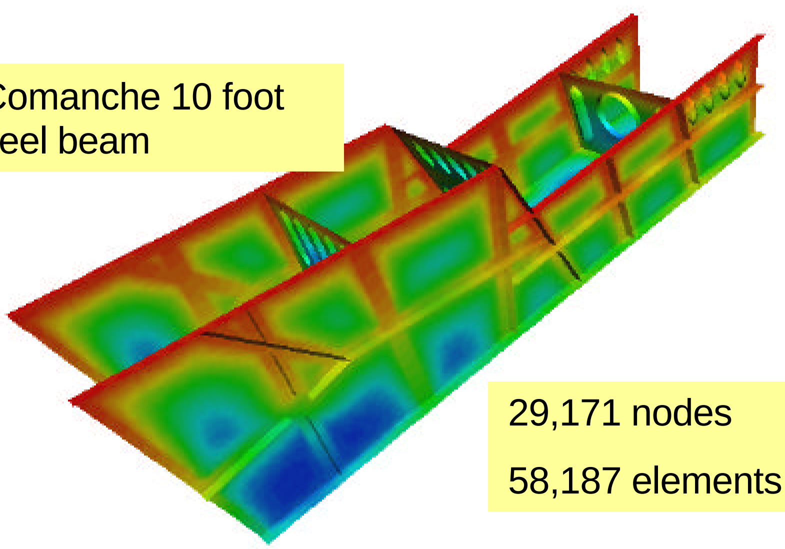
- Discrete equation for P and Ψ: $C_{ii}\Psi_i^{n+1} - C_{ii}\Psi_i^{n} + \Delta t[K]_{ij} P_j = \Delta t\, f_i$
- Both fill factor and the pressure field are solved in a iterative manner

Computational Efficiency

COMPOSE



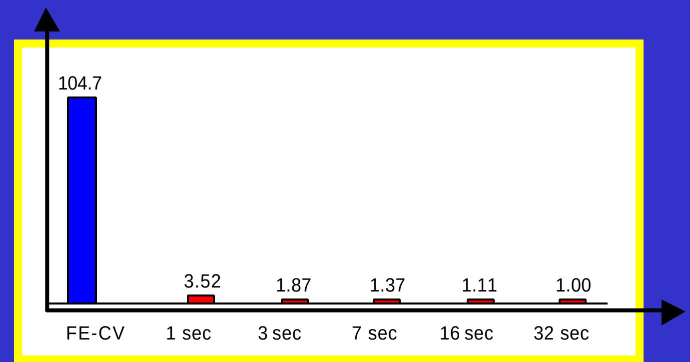
CAV Crew capsule

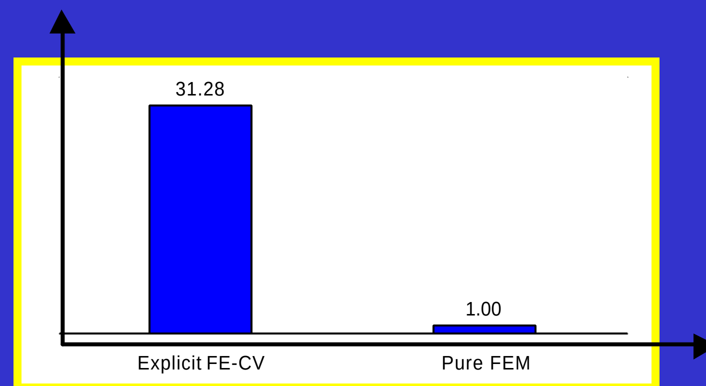


Comanche 10 foot keel beam

29,171 nodes

58,187 elements



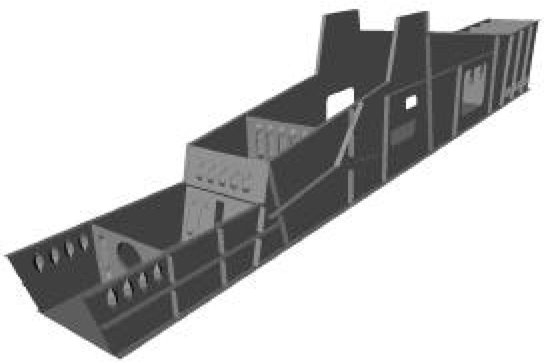


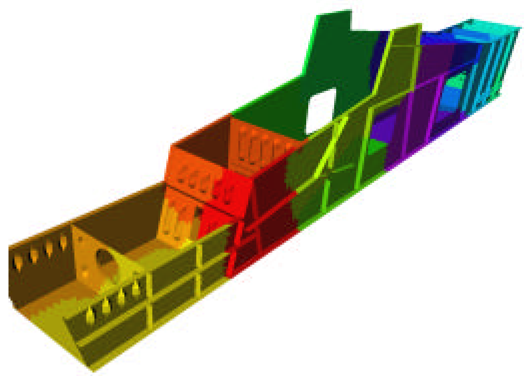
Pure Finite element method is physically accurate; computationally efficient.

Large-scale simulations once impossible with explicit FE-CV are now realistically possible with Pure FEM

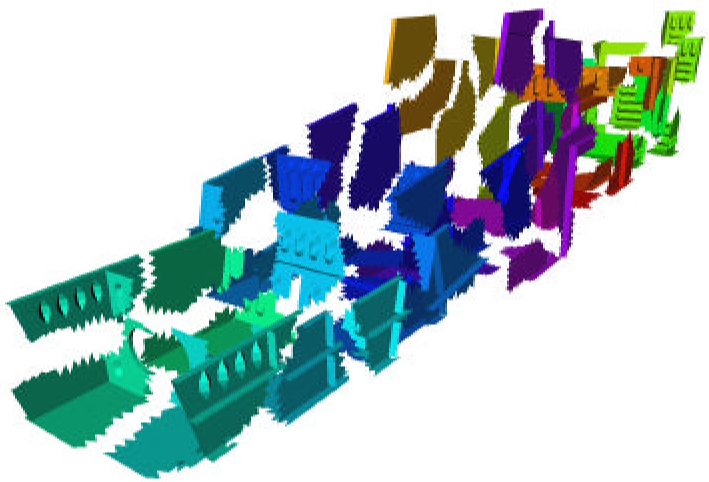
CHSSI Scalable Software Developments

- MPI Scalable Implementation
  - Using Fortran 90.
    - Performance.
    - Expandability.
  - Using ParMETIS and METIS for domain decomposition.



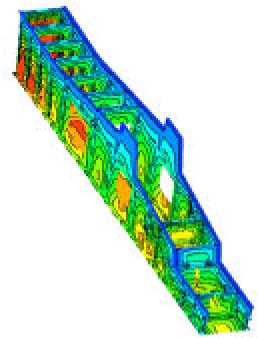


16 Processor Partitioned Domain



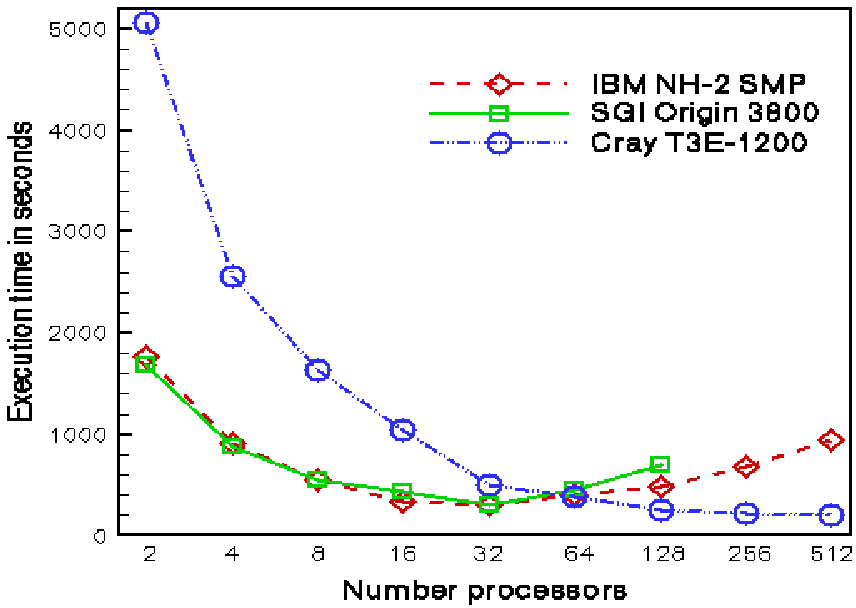
64 Processor Partitions

Scalable MPI Simulations



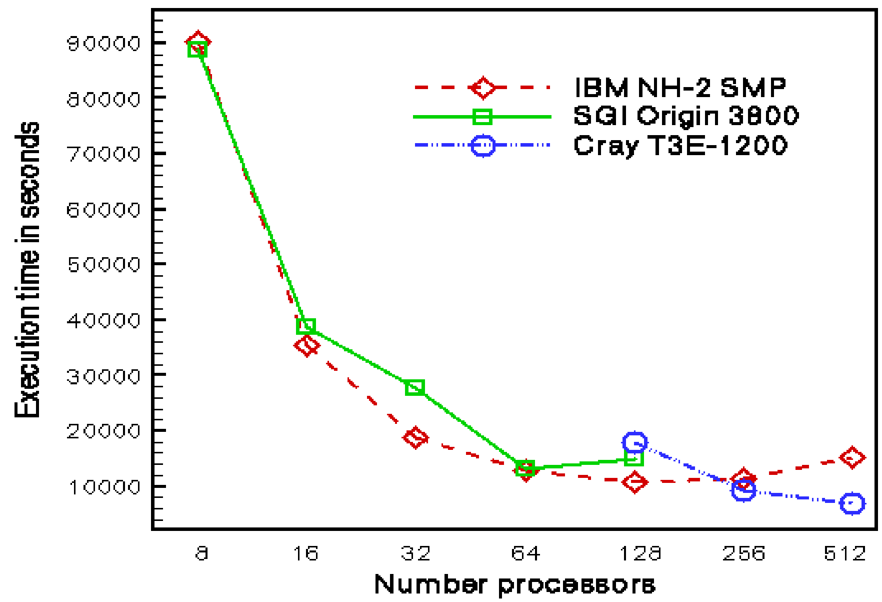
45,547 nodes

89,945 elements



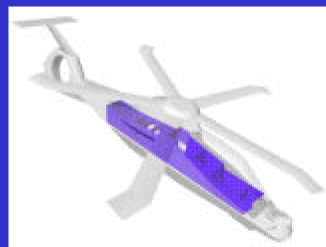
405,327 nodes

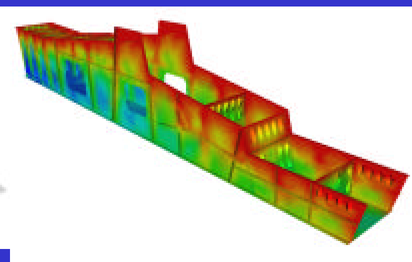
809,505 elements



- Good scalability and portability
- Large scale process modeling and simulations

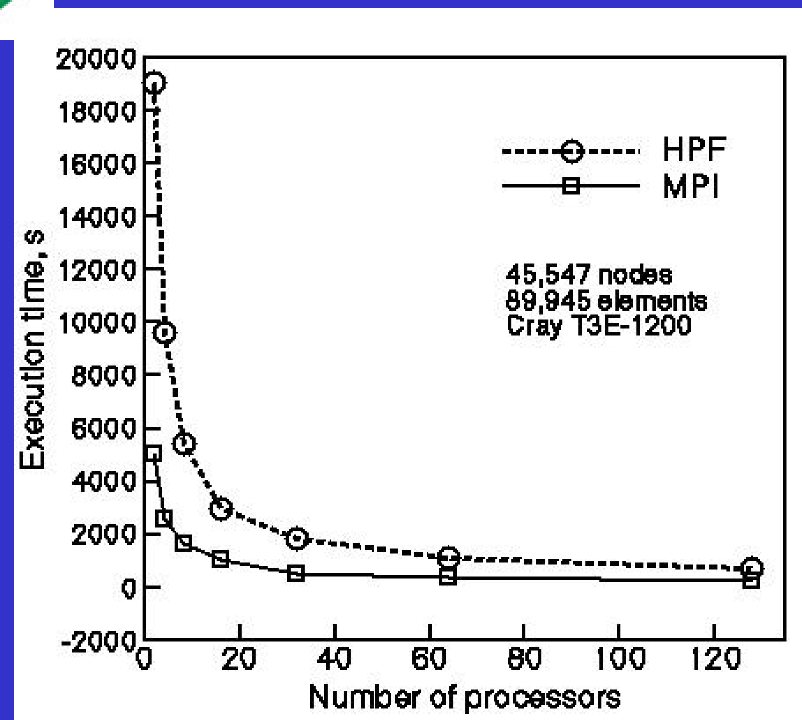
Large-Scale Simulations





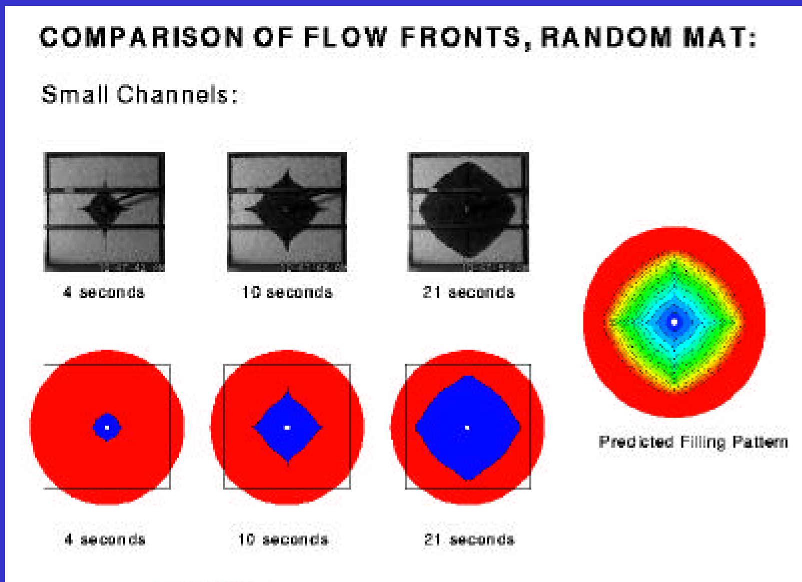
RAH-66 Comanche

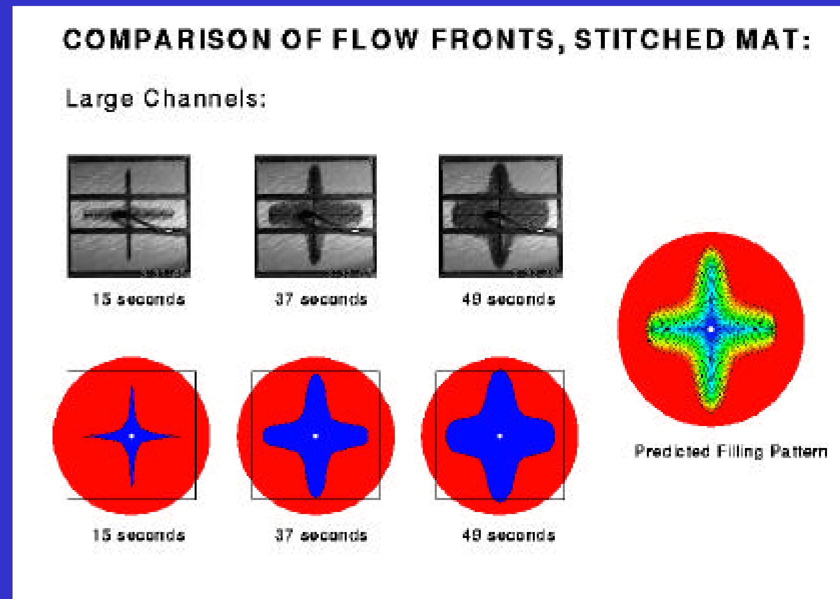
Nodes	Elements	FE-CV	Pure FE
135,492	269,835		
297,576	594,756	X	
405,327	809,505	X	
892,332	1,784,268		

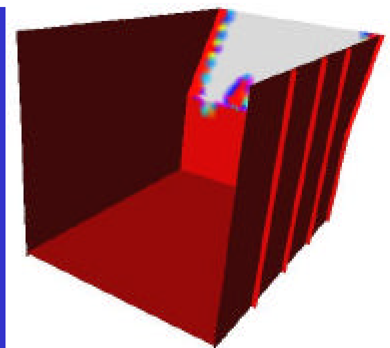


- New computational algorithms (pure FE) and HPC resources enable realistic large-scale process simulations
- Time step increment limitations of FE-CV does not permit realistic simulations

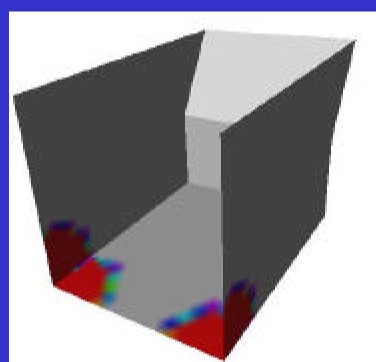
Flow Channel in LCM and Process Models







With channels



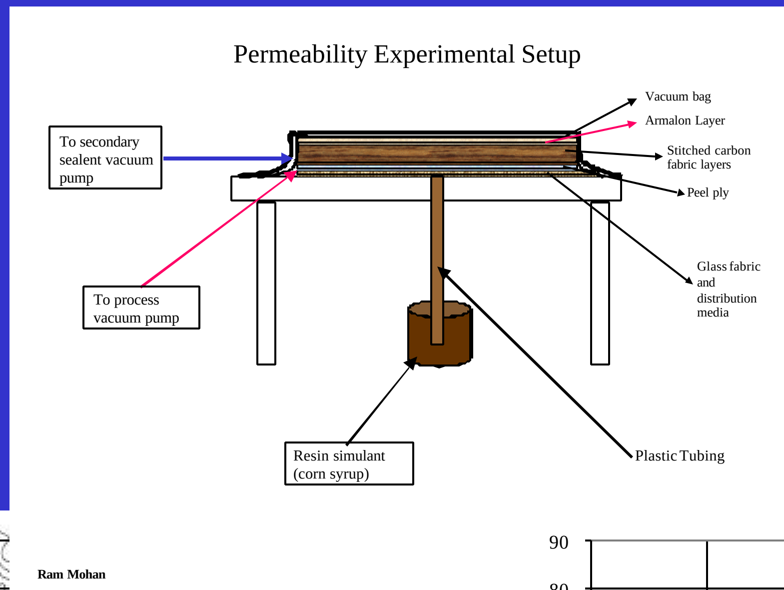
No channels

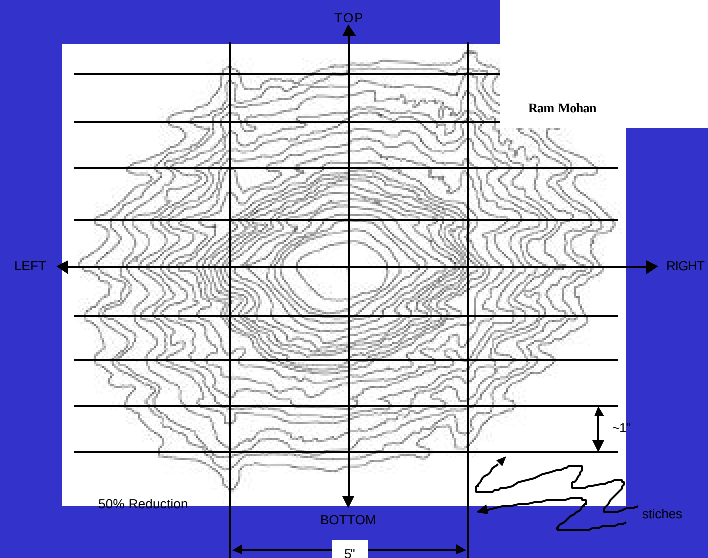
- Flow channels on mold surface improve impregnation
- Experimental comparisons provided permeability characterizations for simulations
- Validations for simulations, material characteristic data

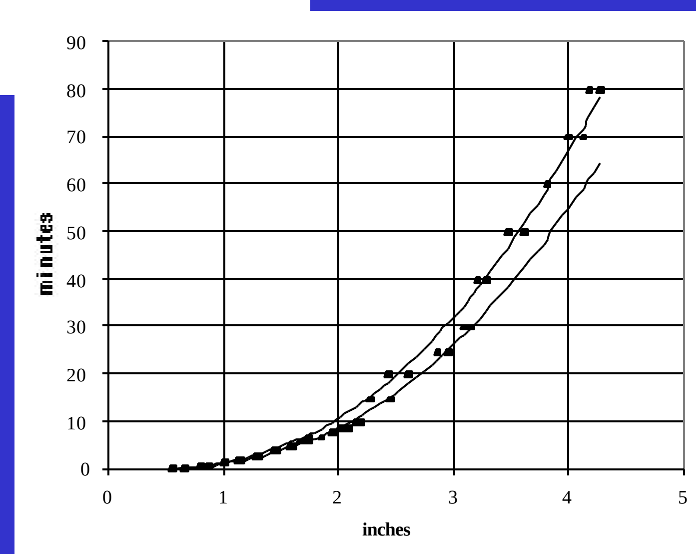
$$K_{equ} = \frac{a^2}{12}\left[1 - \frac{192a}{p^2 b}\sum_{i=1,3,5,\ldots}^{\infty}\frac{\tanh\left(ipb/2a\right)}{i^5}\right]$$

Material Characterization

Experimental Setup



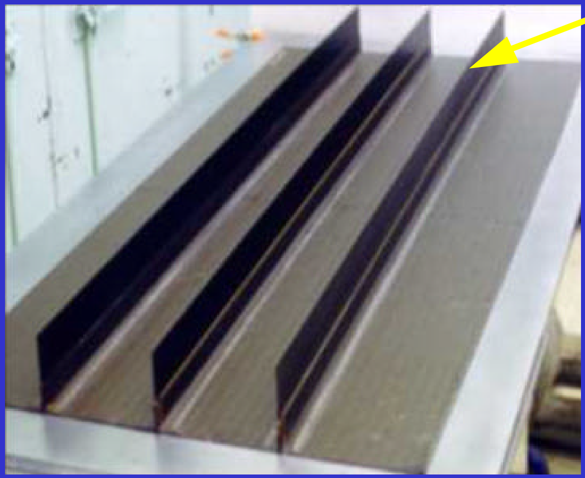




Time dependent flow progression

RWSTD Case Studies

Simple Panel - Actual Fabrication



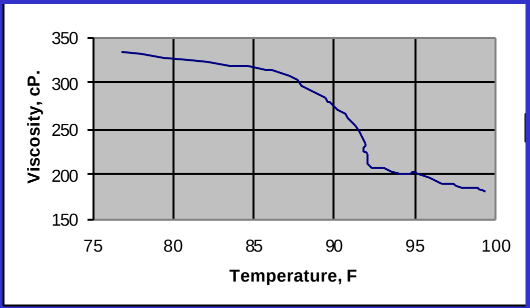
Pre-cured Frame

5 Panels with various fabrication parameters

Good pull-off strength meets design requirement

Viscosity

SI-ZG 5A



2 Injection Processing Configuration

Flow channels were not used during the process

Panels 3 – 5 similar processing configuration; Resin viscosity varies

Panel	Resin Infusion Time
1	**8hrs, 20 minutes**
2	**3 hrs, 34 minutes**
3	**3 hrs, 14 minutes**
4	**2 hrs, 22 minutes**
5	**3 hrs, 40 minutes**

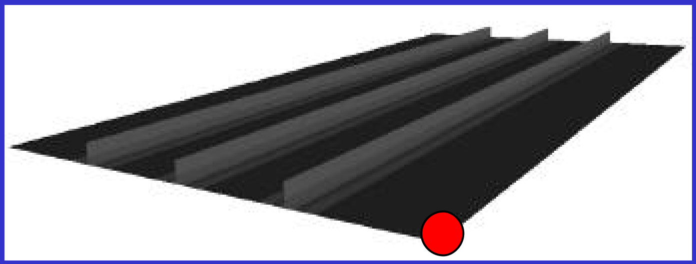
Process Modeling and Simulations

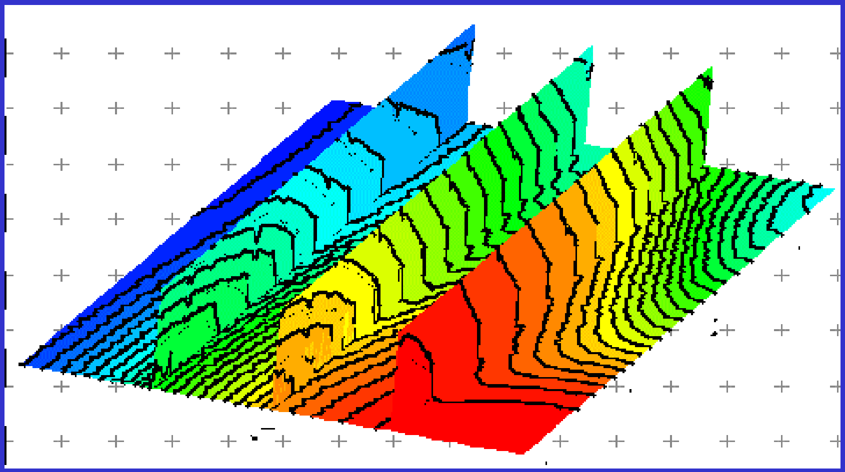
Case Study: Simple Panel

- 5 Different injection processing configurations

Resin Infusion Time

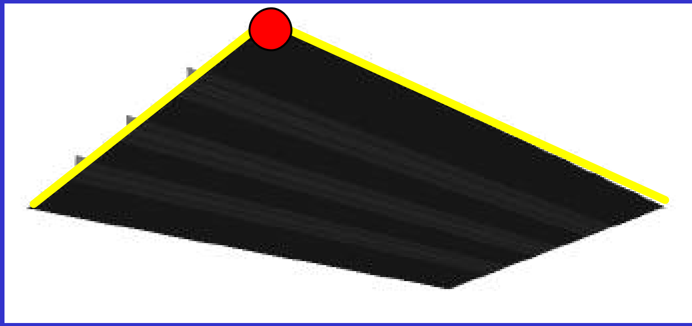
SP-1

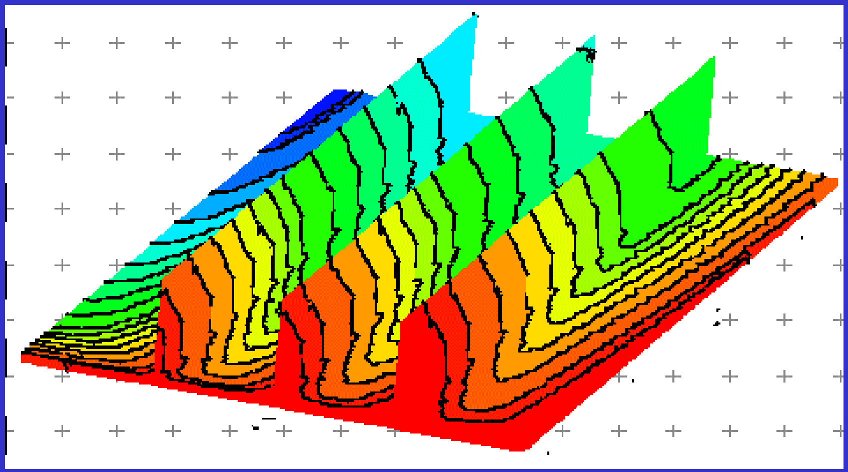




7 hrs, 36 min (simulation)
8 hrs, 20 min (actual)

SP-3 (with channels)





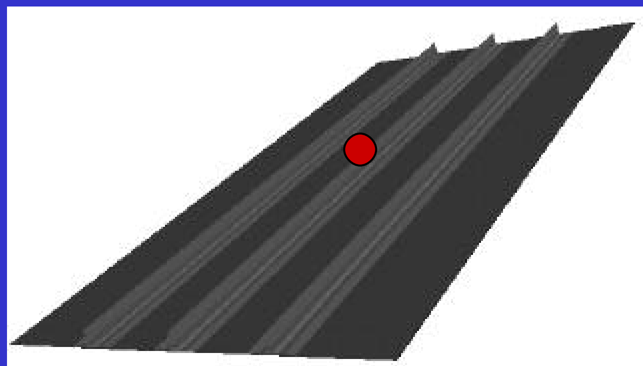
16 min
(simulated)

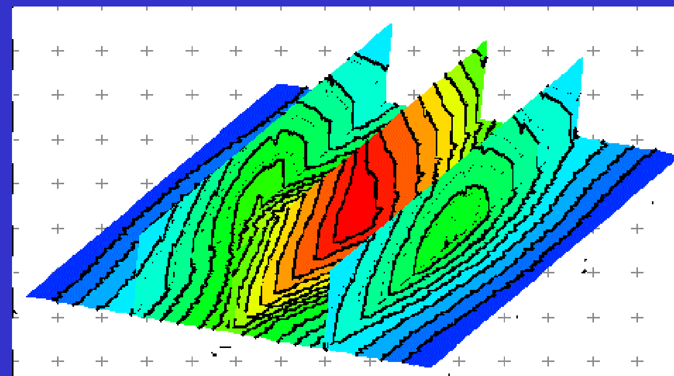
Process Modeling and Simulations

Case Study: Simple Panel

Resin Infusion Time

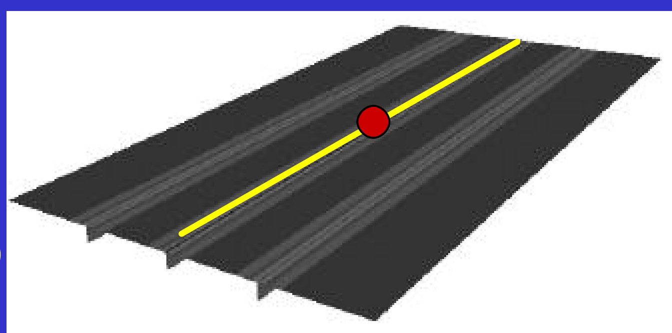
SP-2

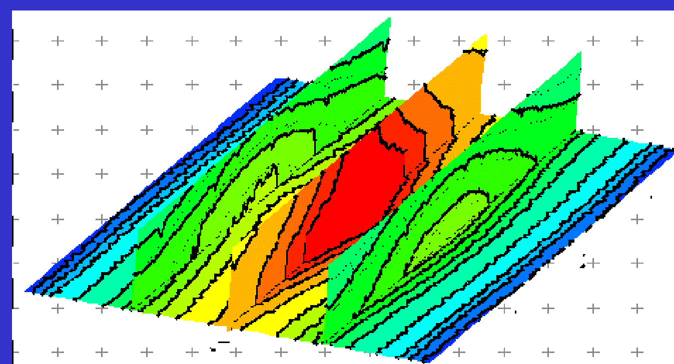




3 hrs, 19 min (simulation)
3 hrs, 30 min (actual)

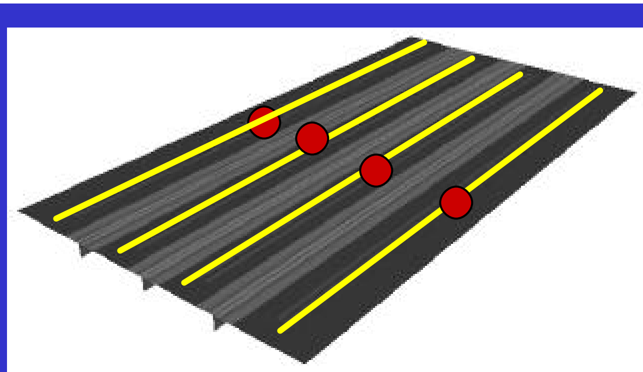
SP-4 (with channels)

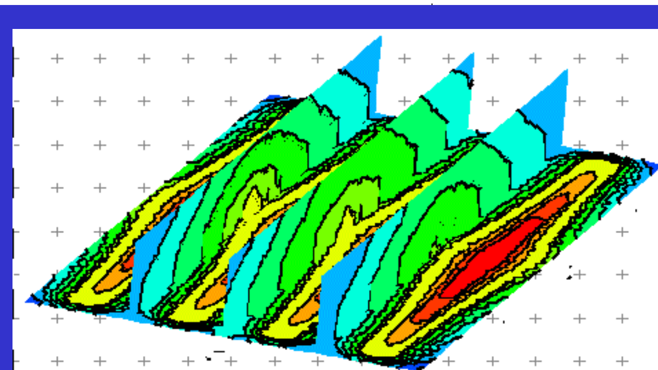




9 min (simulated)

SP-5 (with channels)





1 min, 21 sec (simulated)

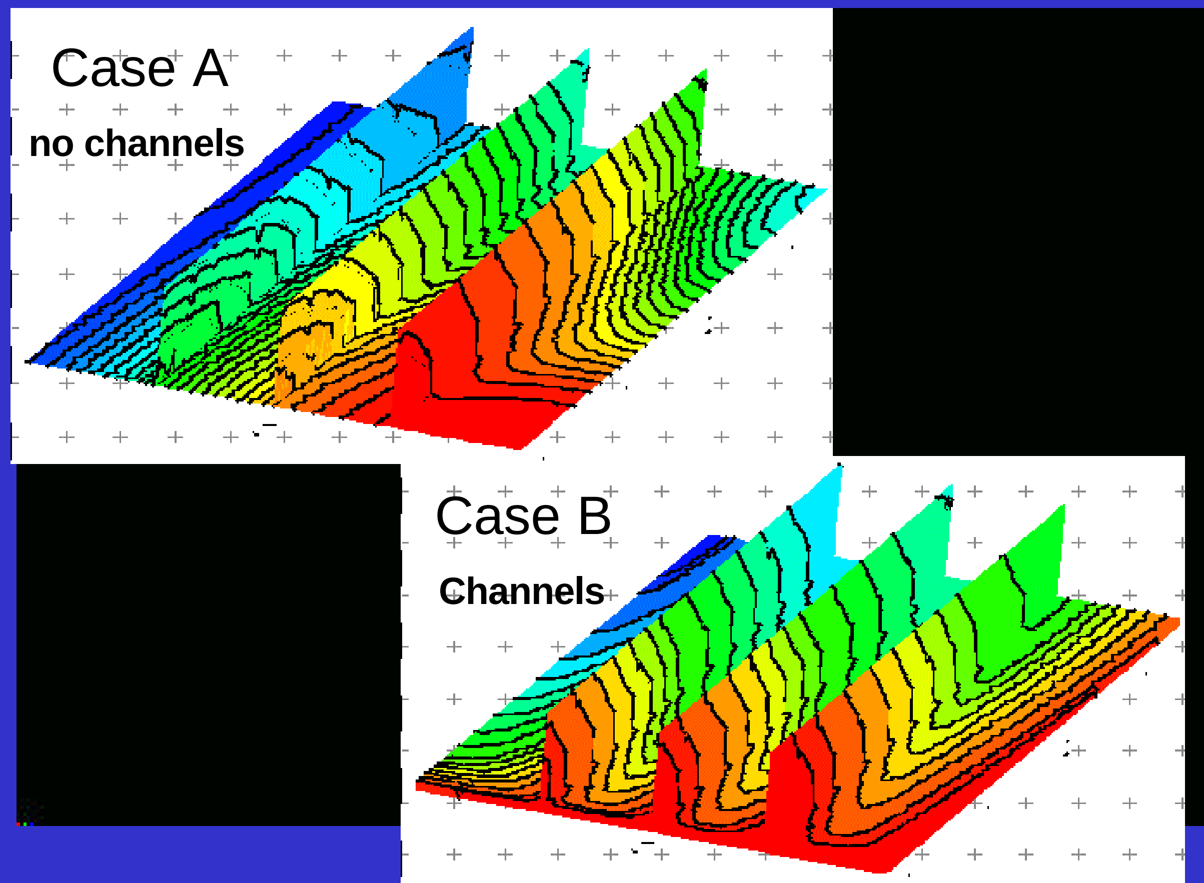
Process Modeling and Simulations

Case Study: Simple Panel

Transient resin progression

Case A: SP – 1

Case B: SP – 3

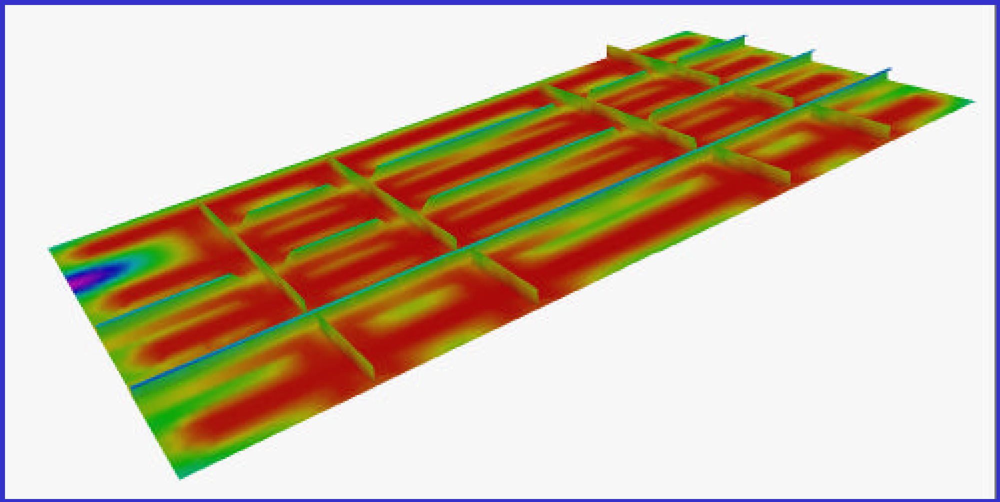


Simulations:

- Validate process models with actual observations
- Can significantly reduce infusion time
- Obtain best process injection and parameters

Demonstrated that the infusion times could have been easily **reduced to less than 2 minutes from > 8 hrs.**

RWSTD Complex Panel

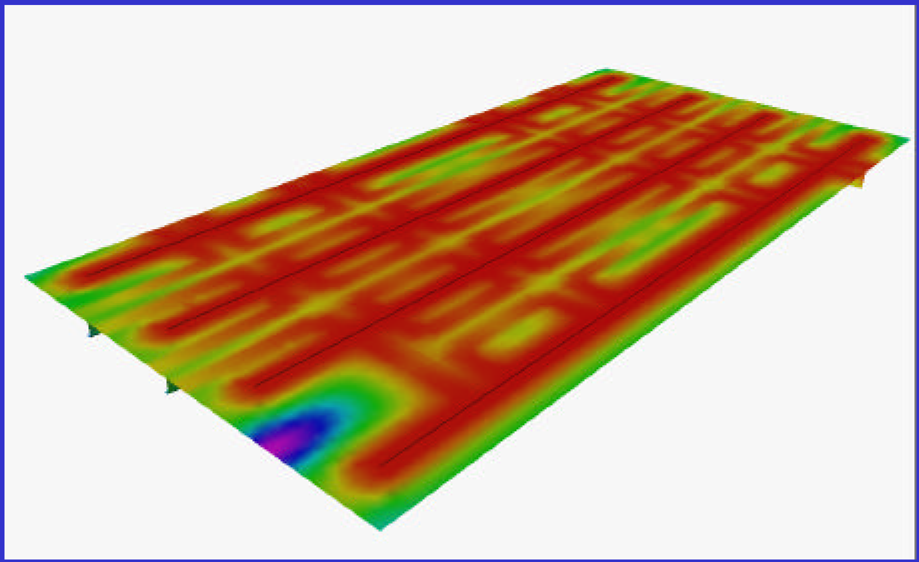


Fill Time:

Simulated: 462 seconds (7 + minutes)

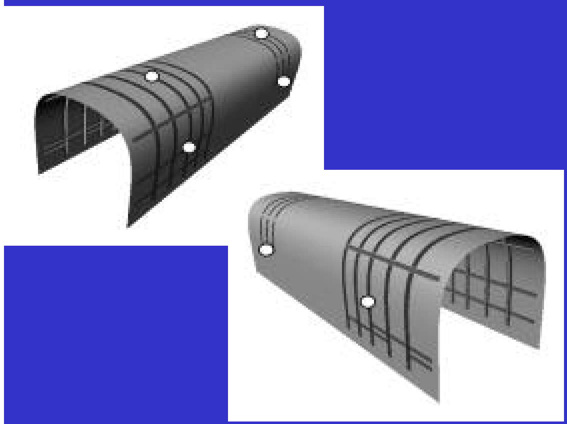
Actual: 6 + minutes (6 - 9 minutes)

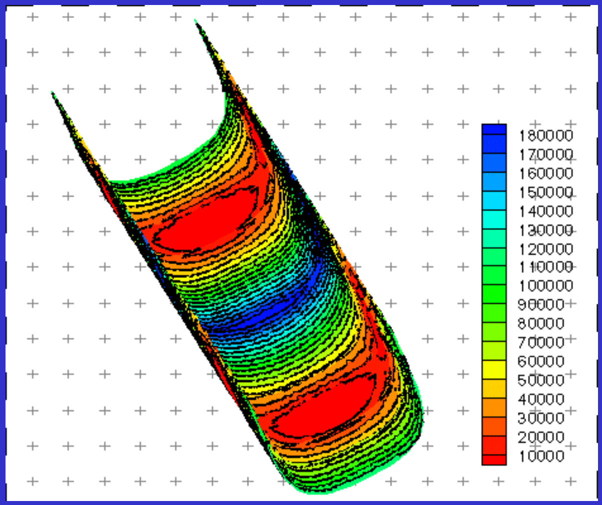
- Involved use of channels
- Model results match well
- V&V for simulations

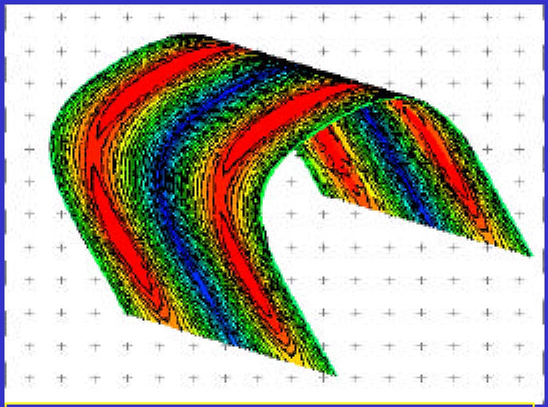


Applications to 14-Foot RWSTD Section

No channels

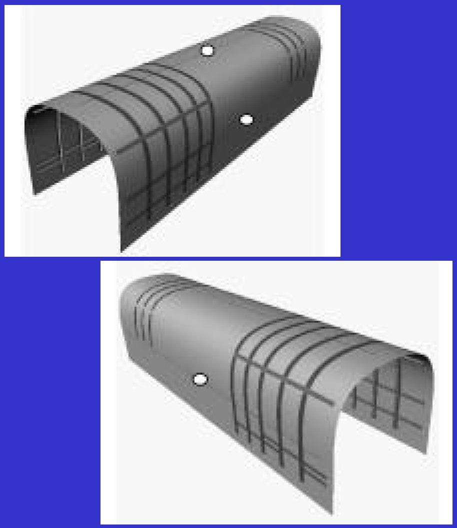


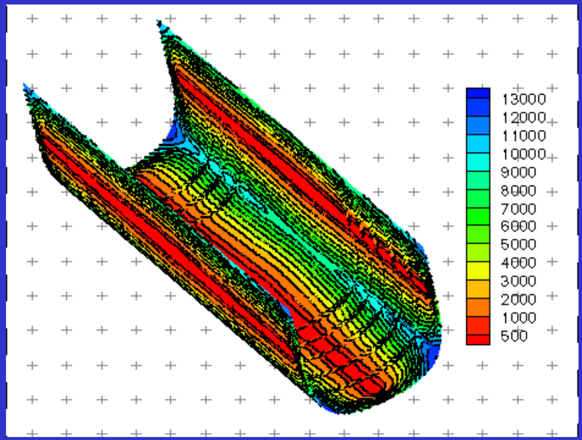


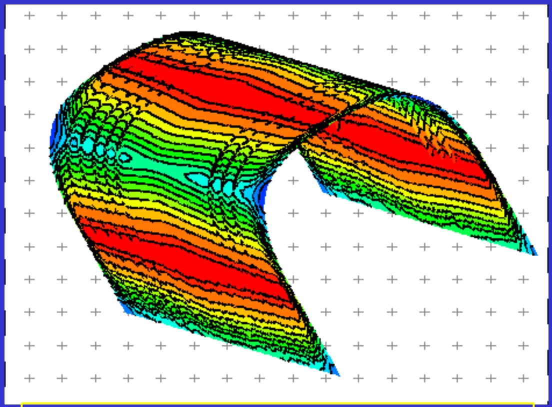


Infusion Time > 50 hrs

With Channels



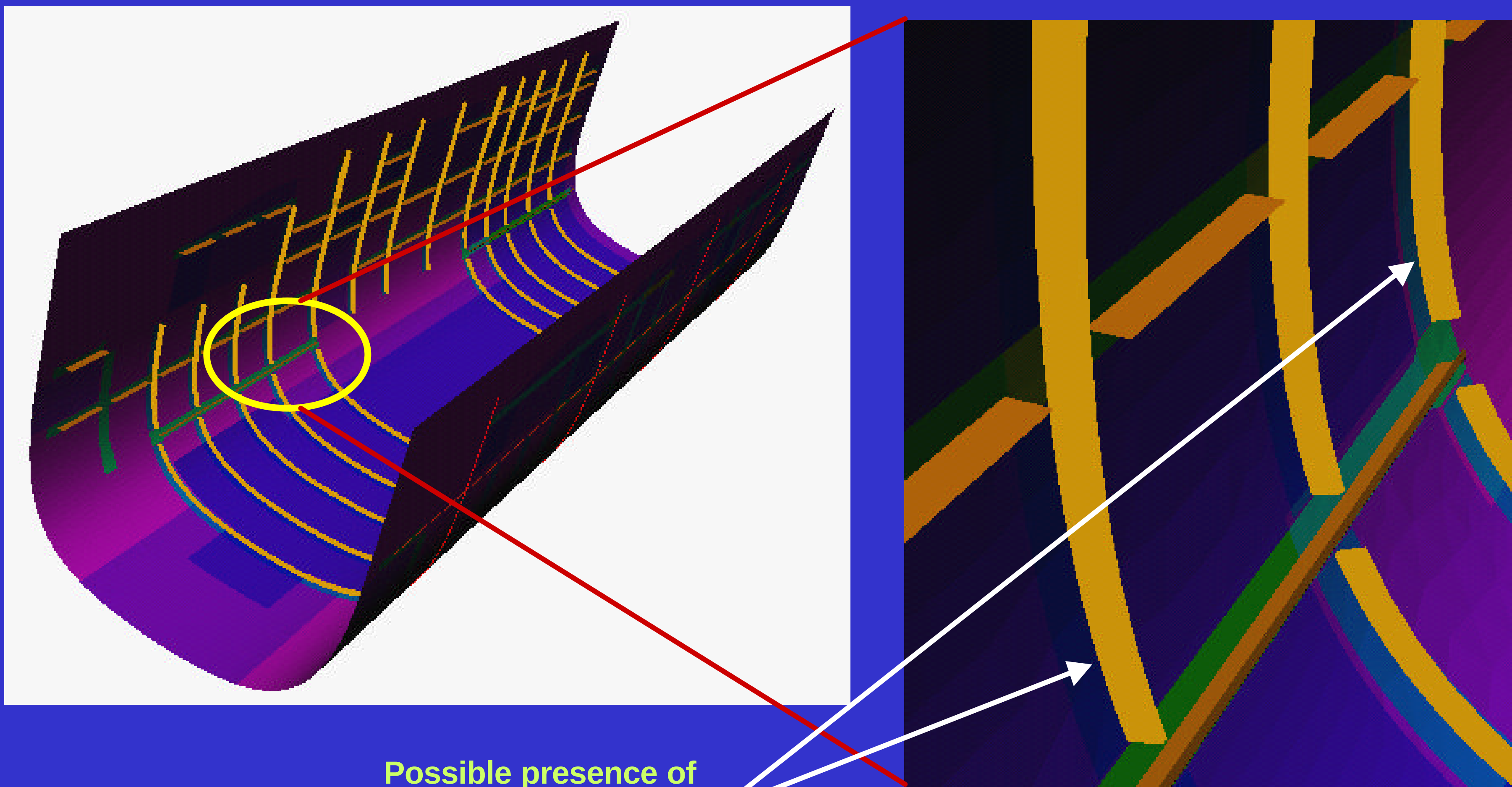




Infusion Time ~3 hrs

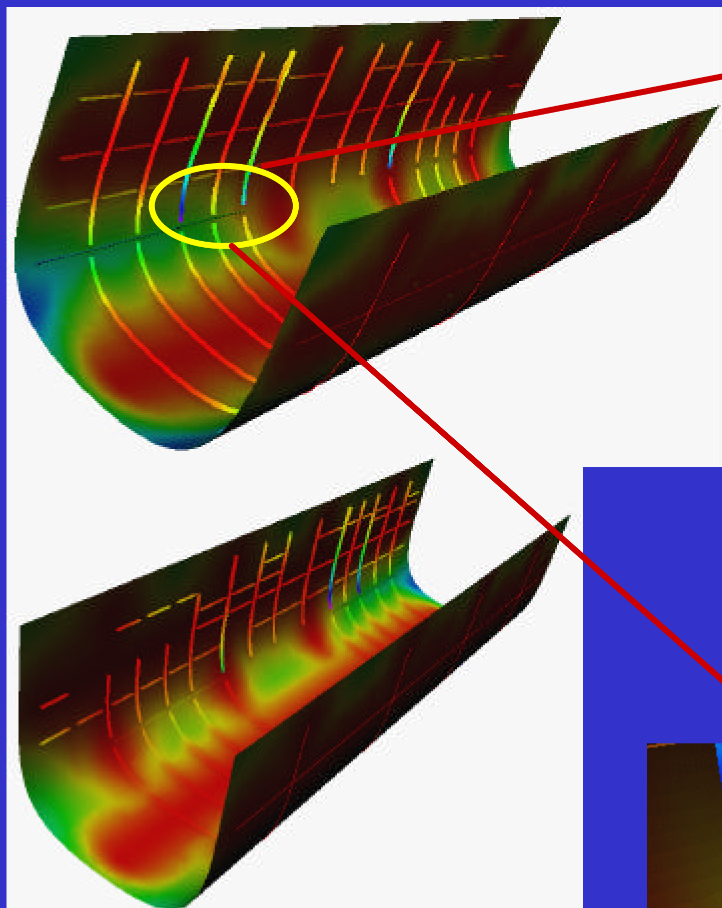
Applications to 14-Foot RWSTD Section

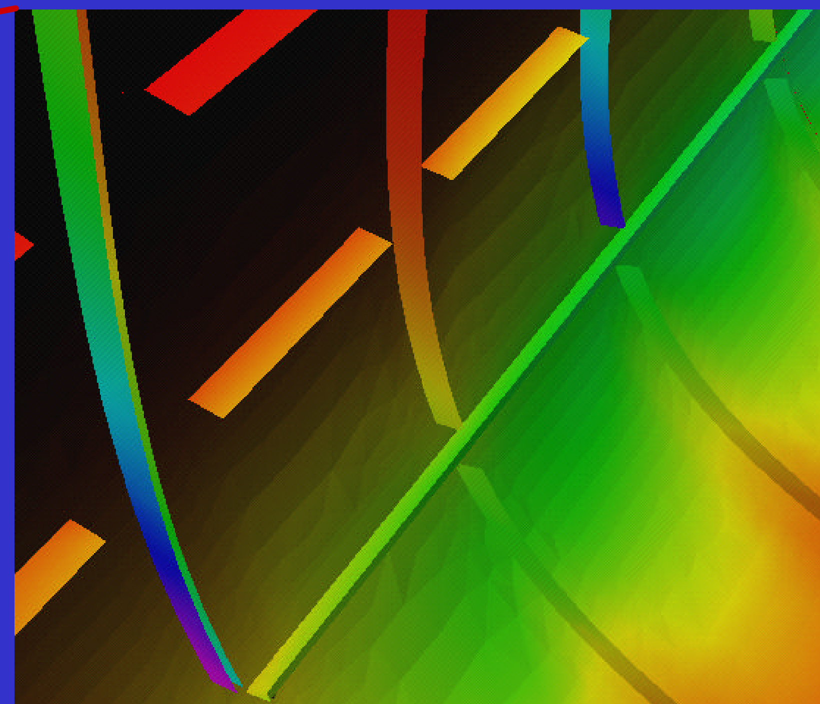
Simulations: Emulate possible processing errors

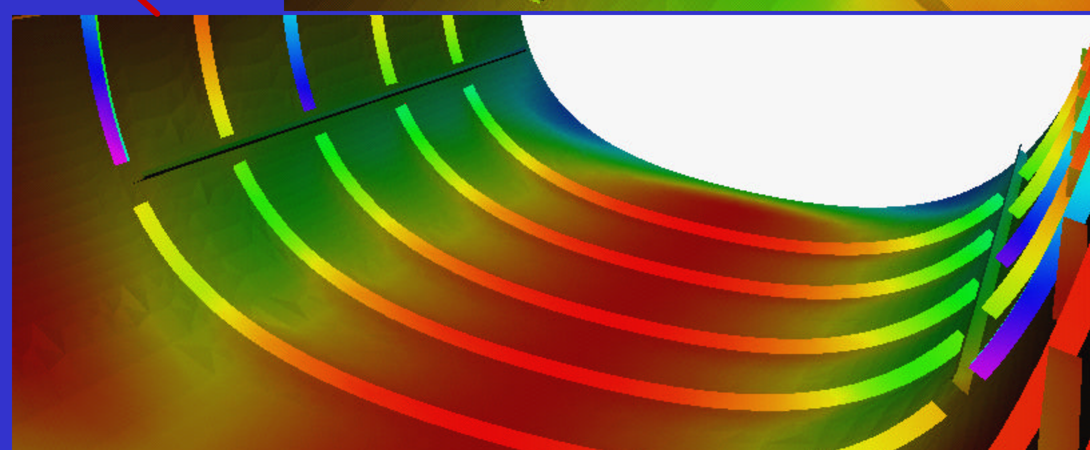


Possible presence of impermeable bagging material underneath

Applications to 14-Foot RWSTD Section







- **Dry spot formation**
- **Actual processing: material and time loss**